ECE 146B: Digital Communication Theory and Techniques
Lab 2: Pulse-Code Modulation (PCM) and Line Codes

Lab Report Due: 5:00 p.m., Friday, April 24, 2009
(Place in the ECE 146B Homework Box on the 3rd Floor of Harold Frank Hall)

1 Objective

The objective of this lab is to study the properties of pulse-code modulation (PCM), using uniform and nonuniform scalar quantization. Different line codes will also be studied.

2 Equipment

Matlab, Simulink, and the Communication Toolbox software are available on the ECI workstations.

3 Background

3.1 Pulse-Code Modulation

Pulse-code modulation (PCM) is an extension of pulse amplitude modulation (PAM) that incorporates quantization of the samples to discrete levels and then a mapping of these levels to a bit stream. Since PCM encodes a message into bits (0s and 1s), it is usually referred to as a source code. PCM does not yield waveforms that vary linearly with the message. As in the case of PAM, the Nyquist sampling rate must be satisfied, i.e., f_s must exceed twice the highest frequency component in the message. PCM offers advantages over analog modulation techniques such as its resistance to transmission noise and its ability to be processed digitally. PCM can be processed entirely in the digital domain, allowing for a range of signal alterations that would otherwise be impossible in the analog domain.

Quantization is the process whereby a continuum of levels is reduced to a finite number of discrete levels. This process is similar to the rounding of fractions to the nearest whole number. Quantization produces a round-off error called quantization distortion, which is referred to as quantization noise. Increasing the number of quantization levels reduces the range of the round-off error, but it is impossible to completely avoid quantization distortion.

An analog-to-digital (A/D) converter is used to convert the continuous message signal into a series of numbers or a group of bits, with each of these representing a level of the quantized message signal. The resulting stream of numbers is the PCM signal. A digital-to-analog (D/A) converter performs the inverse operation of the A/D converter, by changing the stream of numbers to a set of discrete analog voltages (i.e., the quantization levels). The A/D and D/A converters must match

with respect to word size, sampling rate, and mapping in order for the PCM signal to be properly demodulated.

3.2   Line Codes

When transmitting a binary sequence, the line code determines specifically how the 0s and 1s should be represented. In unipolar, for example, a 1 is represented by a positive pulse while a 0 is represented by no pulse (zero level). The line code affects the transmitted signal in several important ways. These include the resulting shape of the power spectral density (PSD) of the transmitted signal, the type of symbol synchronization (timing), and the use of AC or DC coupling.

3.3   Eye Pattern

The eye pattern of the received signal is an effective means of illustrating the severity of intersymbol interference (ISI) and noise caused by the channel, as well as the sensitivity to timing errors (called jitter). An oscilloscope can be used to display the received signal when it is triggered at the symbol rate $1/T$.

4   Preparation

1. How many bits are required to represent an analog signal with values ranging from -1 to 1 if the resulting quantized signal is to have a resolution of 0.125?

2. Assuming a maximum source coding data rate of 50 kbits/sec, what is the maximum signal bandwidth that can be transmitted using PCM with the number of bits found in Question 1? What is the corresponding Nyquist rate?

3. For the results obtained for Questions 1 and 2, compute the signal-to-quantization noise ratio (SQNR) of the system assuming that the message signal has a peak-to-average power ratio of 3 dB and then 14 dB.

4. Generate 1000 samples of a zero-mean Gaussian random process that has variance $\sigma^2 = 2$. For a uniform quantizer with 32 levels, compute the corresponding SQNR. Plot the first 10 samples of the random process, along with the corresponding quantized values and the quantization error.

5. Repeat the previous exercise using a nonuniform μ-law quantizer with $\mu = 255$.

5   Procedure

Simulations of the systems below are easiest to build and analyze using Simulink. In addition, it is important to always work with your sample time colors on because the systems below make use of multiple data rates. This helps to avoid any undesired interpolation/decimation which can affect your results. The zero-order hold (ZOH) block will be used extensively to convert data rates. Note the following relationships: message bandwidth < Nyquist sampling rate < source code data rate (PCM) < line code data rate. For consistency, run each simulation for the same length of time.

Note the following definitions for your measurements: SNR = 10log10(average signal power/average noise power), SQNR = 10log10(average signal power/average quantization noise power).

5.1 PCM with Uniform Quantization

Design and test a 4-bit PCM system with uniform quantization to encode and decode an audio signal and a sine-wave signal (440 Hz, 0.8 V peak-to-peak). Use 50 kbits/sec for your source-coding rate. Measure the power of each message signal and the corresponding quantization noise.

(1) What is the SQNR of your 4-bit PCM system for the audio and sine-wave signals? How do your results compare with your calculations in the Preparation section? Explain why you think there are differences.

(2) Examine the spectrum of the quantization noise for the audio and sine-wave signals. Do the results suggest that the noise is statistically independent of the message? Why or why not?

5.2 PCM with μ-Law Quantizer

Design and test a 4-bit nonuniform PCM system using a μ-law compressor and expander (compander). Test your system using the audio and sine-wave signals from the previous section. Choose a value for μ which you think will work best for the audio signal.

(3) What value of μ did you choose and why?

(4) What is the SQNR for the audio and sine-wave signals? Compare your results with those in Question 1. For which message signal do you achieve the largest performance gain and why?

5.3 Line Coding

To test the performance of the various line codes, use a random bit message constructed from a sampled sequence of a white noise process. Eye patterns will be used to help examine the characteristics of each line code. Use a sampling time corresponding to $10\times$ the rate of the source code in order to allow analysis of the frequency response and the eye pattern.

5.3.1 On-Off Signaling

Design an on-off signaling coder and decoder block that transmits a 1 as 1 V and a 0 as 0 V.

5.3.2 Non-Return to Zero (NRZ)

Design a non-return to zero coder and decoder block that transmits a 1 as 1 V and a 0 as −1 V.

5.3.3 Quaternary PAM

Design a quaternary PAM encoder and decoder block that transmits 00 as −1.5 V, 01 as −0.5 V, 10 as +0.5 V, and 11 as +1.5 V. Note that the symbol duration of the quaternary PAM system will be twice the bit duration of the source code.

(5) Test your coders and decoders using the random bit message. You can check your results by subtracting the input from the output. Observe the coded signals in the time and frequency domains. Comparing the outputs of the different encoders, which uses more power? Which codes have a significant DC component? Which codes use more bandwidth?

(6) Do the observed spectra suggest that the coded signals are created from a sampled sequence of a white-noise process? Explain why or why not.

5.4 Eye Patterns

For the NRZ and quaternary PAM signaling, include additive white Gaussian noise (AWGN) with the encoded signals and examine the resulting eye patterns. Note that the noise should be added using the same sampling time as the line code (i.e., $10\times$ the rate of the source code).

(7) From the eye patterns, determine the level of the noise power for each signal for which you think errors will result at the receiver. What noise powers did you choose? With this noise power, measure the SNR of the encoded signal for the NRZ and quaternary PAM signals. Include this data and a plot of the eye patterns in your lab report.

(8) Examine the spectra of the encoded signals plus noise for the NRZ and quaternary PAM signals with the noise you chose in the previous question. How are the results different from what you observed in the noise-free case? Do you see the message in the spectrum?

6 Lab Report

Please include the following in your lab report.

1. Include printouts of all Simulink block diagrams that you designed.

2. Answer all questions (in the Preparation and Procedure sections) and back them up with results, analysis, theory, and any computations.

3. Write a paragraph about questions and confusions that you experienced in this lab.